Presentation of a Test Rig to Record Mass Flow Rate, Pressures and Temperatures of a Household Refrigerator During On/Off Cycling Mode

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ABSTRACT

In this paper a test rig for obtaining data on the operation of a household refrigerator is being presented. Therefore sensors for measuring pressure and temperature, as well as the mass flow rate were introduced into the refrigeration lines. Also the power consumption of the compressor was measured. In order to avoid effects of a changing ambient temperature the test-refrigerator was placed inside an environmental chamber. All probes were connected to an automatic data acquisition system using a PC as user interface. A software was developed to enable the data storage as well as putting them on screen for instant process analysis. We used the system to collect data on the on - off cycling behavior of a particular household refrigerator, which we want to simulate numerically.

1 INTRODUCTION

In order to develop a simulation software to forecast the energy consumption and cabinet temperature of a refrigerator that exists only in the drawings of the R&D engineer one needs data, actual measurement. Right now it is still a common procedure to build the refrigerator and measure and test and modify it in order to reduce energy consumption and change the temperature distribution in the refrigerated cabinet. Simulation software is seldom used. Although it takes longer to build a numerical model of a refrigerator it is worthwhile Many of the modifications which will be possible to reduce energy consumption contribute relatively little, but in sum the savings could be remarkable. A simulation model is a valuable tool to investigate those modifications. This paper is intended to acquaint you with a test rig to get to those data series, which are needed to program the simulation software.

2 SETUP OF THE TEST RIG

The test refrigerator is a standard one-temperature refrigerator. It has a refrigerated volume of 178 l and a rated energy consumption of 0.57 kWh/24h. Refrigerant used in the cycle is isobutane, the amount is 20 g. The reciprocating compressor uses as lubricant 250 g of a mineral oil with a viscosity of 32 /4/. Heat transfer to the evaporator and from the condenser is done by free convection at the airside. The measurement conditions were set according to DIN EN 153 (European standard for measuring the energy consumption of electric mains operated household refrigerators).

One of the points to emphasize on was not to disturb the dynamic behavior of this small scale refrigeration system.

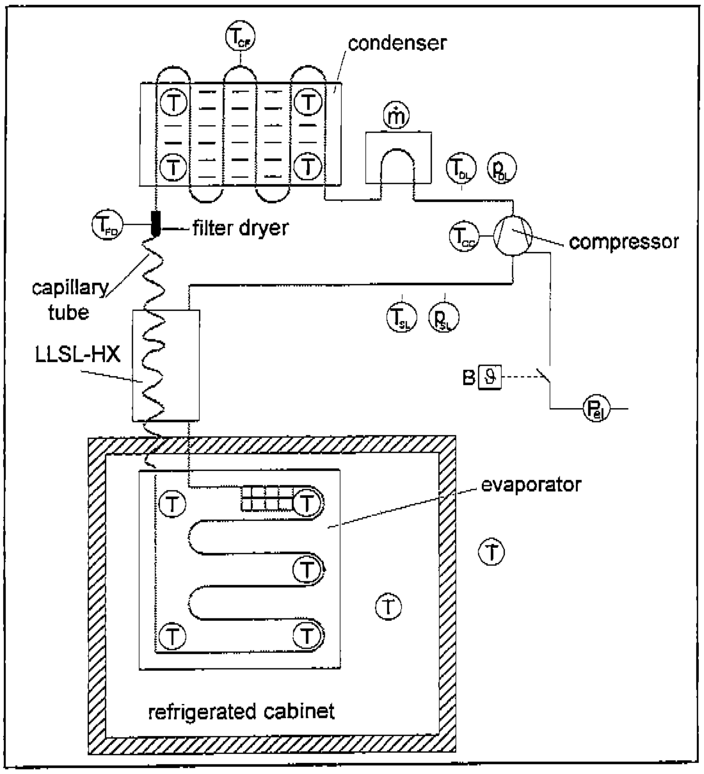

fig. 1 test rig

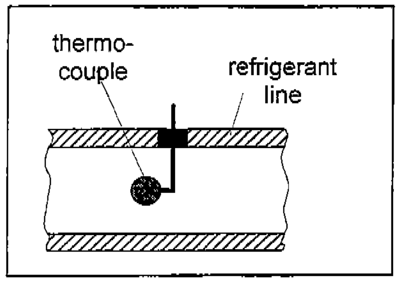

fig. 2a TC in refrigeration line

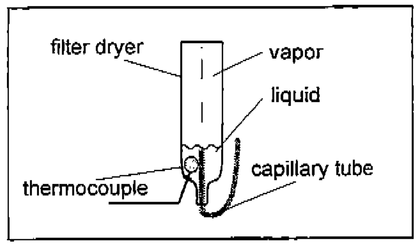

fig 2b TC in filter dryer

There are four thermocouples (TC) glued into the refrigerant lines, one at the discharge line of the compressor (T_{DC}), one at the suction line (T_{SL}), one at the filter dryer (T_{FD})(fig.2b)and finally another one in the middle of the condenser (T_{CF})(fig.2a). Other TCs are glued on the heat exchanging surfaces of condenser, evaporator and compressor can. Three TCs are set up in different locations of the cabinet (according to DIN EN 153) to record the mean temperature there. Two pressure transducers are connected one to the suction line of the compressor and the other one to the discharge line, both at a distance of 300 mm from the compressor can. We used a capillary tube to connect transducer and refrigeration pipe, thus avoiding directly clamping heat capacities onto the pipes.

3 OBTAINING THE MASS FLOW RATE

For the dynamic simulation of transport process systems the mass flow rate in each individual component of the system is a vital information, it directly enters into the equations (mass, energy and momentum). But placing a flow meter into every connecting line of the refrigerator components (capillary tube, evaporator, compressor and condenser) would change the dynamic behavior of the system. We therefore have to choose a location, where it is both, useful as well as the possibility of a accurate measurement given. Also we wanted to obtain the mass flow rate directly rather than calculating it from the volume flow rate, because this would introduce more errors. Two principles to measure mass flow rate were investigated. First was to use the effect of changing fluid temperatures with changing mass flow rates, given a constant heat source, as in thermal flowmeters. The other principle is applied in the coriolis force flow meter. It uses the force which develops on the vibrating U-tube as a result of accelerating or decelerating the fluid particles in proportion to the mass flow rate and the angular velocity of the flow. Both meters cause problems if introduced to two phase flow. The coriolis flow meter (CFM) was chosen, because of its high accuracy and low pressure drops. Because the CFM needs higher densities of refrigerant in order to get a reasonable accuracy, we put it between the compressor and the condenser.

4 SETUP OF THE DATA ACQUISITION UNIT

To get all data points at a fixed point in time was not possible, in order to get them with little time delay we chose the following setup (fig.3):

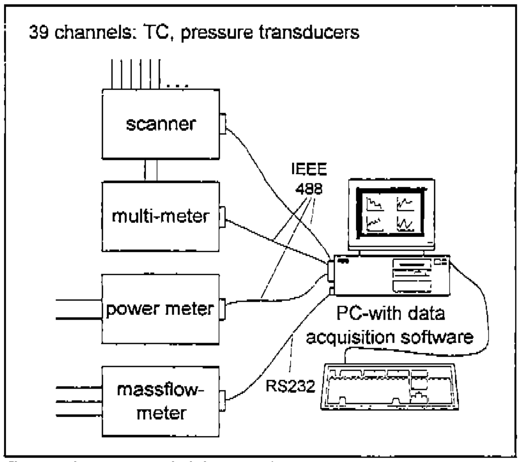

fig. 3 data acquisition unit

TC and PT were connected to a scanner card with a reference temperature sensor. This card was connected to a fast multimeter and the readings were acquired by the computer over one of its ports. A software was developed to run on the PC and serve as a user interface. Also the mass flow meter and the power meter are using the computer ports. Using this configuration a trigger signal from the software will start scanner, multimeter, power meter and mass flow meter at the same instant. The software than takes the readings from the instruments writes them to a computer file and displays the significant ones for process observation. The speed of acquisition can be set to a maximum of one scan per second using the accuracy specification as in 5.

5 ACCURACY AND DYNAMIC BEHAVIOR OF THE MEASUREMENT DEVICES

Thermocouples (TC)

The TCs used have an accuracy of 0.2K, the time constants of the tip is 0.5s for a error of 1% of the total temperature change (see following equation from /1/).

Assumptions: $\alpha = 100\ W/(m^2K)$
$d = 0.002m$

$$f = (T_U - T_M) / T_U \qquad \text{with} \qquad f = \exp\left(-\frac{t \cdot A_O \cdot \alpha}{V \cdot \rho \cdot c_p}\right)$$

with α ... heat transfer coefficient
d ... diameter of TC tip
A_0 ... surface area of tip
V ... volume of tip
ρ ... density of tip material (iron)
c_p ... specific heat capacity (iron)
T_U ... temperature of fluid
T_M ... temperature of tip

Pressure transducers (PT)

The transducers have a time constants of 3ms and are rated to a accuracy of 0.3% of the range, which is in absolute terms:

Low pressure side: 0...6 bar	maximal error = 18 mbar
High pressure side: 0...16 bar	maximal error = 48 mbar

Mass flow meter

The accuracy of the meter depends on the actual mass flow rate. For 20g/min the meter was calibrated but for the much lower flow rates we had to get our own calibration curve using a scale and a can with butane. The display of the mass flow meter has a integrating counter. We connected flow meter and can and compared the integrating counter to the loss of weight of the can on the scale. The time constant of the meter is high, because it internally builds a moving average of 64 measure cycles which is 5.6 s. The pressure drop of the meter is ≤ 20 mbar.

Power meter

The power meter is rated to a accuracy of 0.3 % of the measure range which is in absolute terms ±1 W.

6 ENERGY BALANCE OF THE REFRIGERATOR NEAR STEADY STATE

In order verify the data points and perform an energy balance we set the temperature dial at minimal cabinet

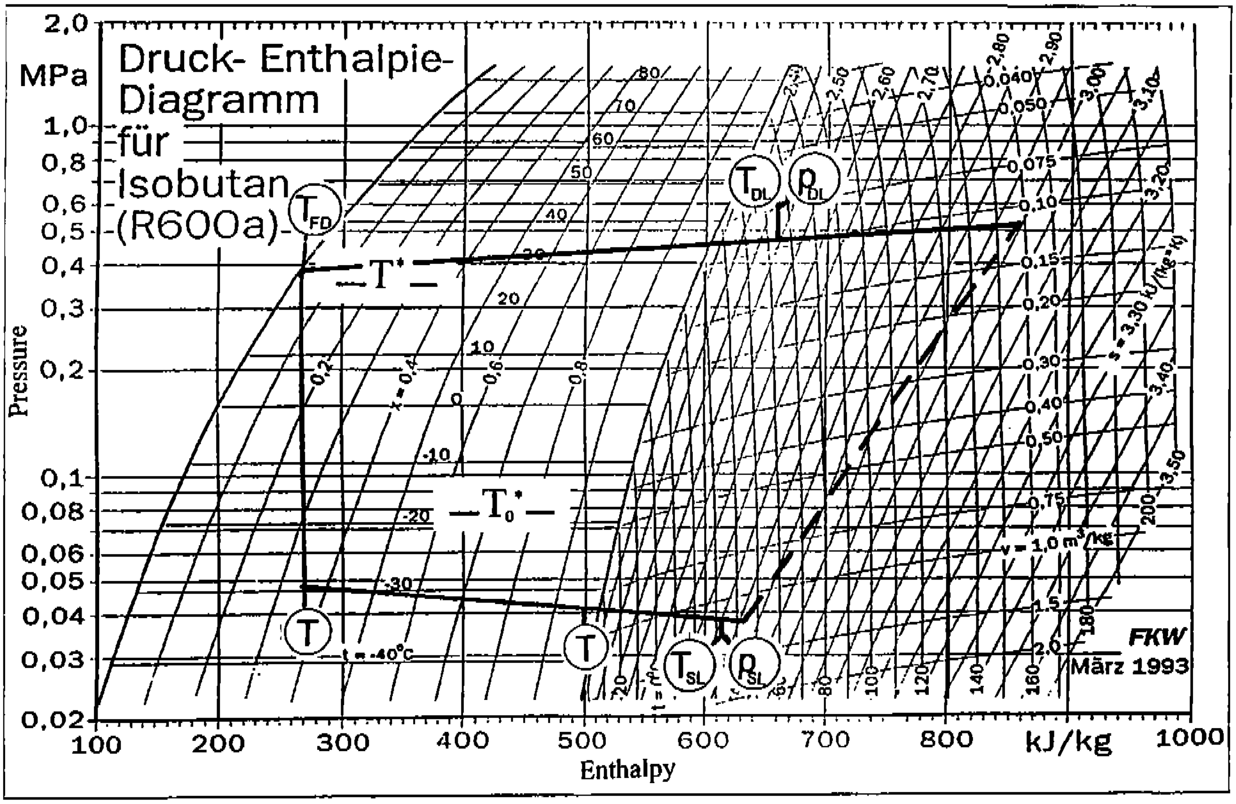

fig. 4 process near steady state in the log p - h diagram

temperature and took the data after a near steady state condition was reached. For simplicity reasons, the cooling of the two phase flow in the capillary tube was neglected in the balance (LLSL-HX). Pressures are stable and there is no refrigerant evaporating out of the oil in the can. (see fig. 7) with the pressure being 0.35 bar and the can surface temperature of 60 °C.

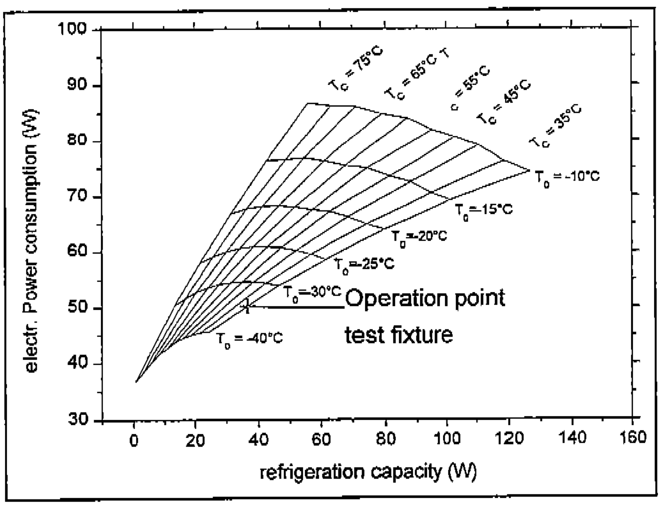

fig. 5 compressor map /4/

Other data we used for this energy balance:

mass flow rate = 9 g/min
mean cabinet temperature = -19 °C

With assuming a temperature difference of 10 K between the cabinet temperature and the refrigerant leaving the evaporator, we calculate a refrigeration capacity of 40 W. Since we assume equilibrium state we compare it with a load calculation of the refrigerated cabinet using EPA refrigerator analysis /2/. We obtain a cabinet constant of 1.1 W/K (heat load through cabinet walls in respect to the temperature difference between ambient and cabinet) from our balance and 1.03 W/K from /2/. We also compared this data to the compressor map of the refrigerator (fig. 5). We find, that the result obtained using our test fixture compared to the conventional method (calorimeter) differs in refrigeration capacity by 12%. Given the accuracy of the sensors and the assumptions taken this difference is acceptable.

7 DYNAMIC BEHAVIOR OF THE SYSTEM

We set the temperature dial to a cabinet temperature of about 5°C and the ambient temperature to 25°C. In figure 6 we see the mass flow rate in correlation with the pressure in the suction line of the refrigerator. As the compressor is switched on the mass flow rate raises sharply to about 30 g/min for a period of 0.4 min. During this time about 9 g of refrigerant is pumped to the condenser. From the vapor pressure diagram of the refrigerant-oil mixture (fig. 7) we can conclude, that about another 10 g are in solution with the oil at the time before the compressor is started.

Now as the oil is heating up and the pressure in the can decreases therefrigerant in solution with the oil starts to desorb and it is being added to the circulating refrigerant. We can see this as the mass flow rate increases at a time of about 1.3 minutes after the compressor started. Also because by now refrigerant at boiling condition is at the entry of the capillary the mass flow into the evaporator increases and therefore the pressure in it goes up.

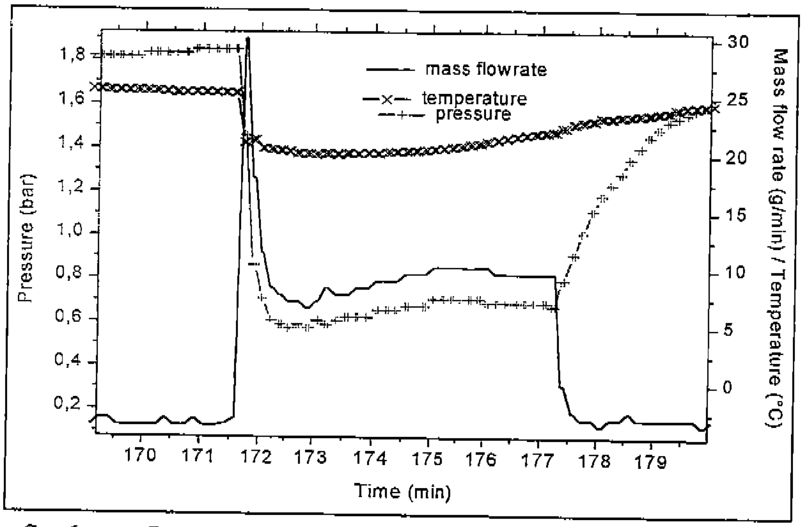

fig. 6 mass flow rate, suction line temperature and pressure vs. time

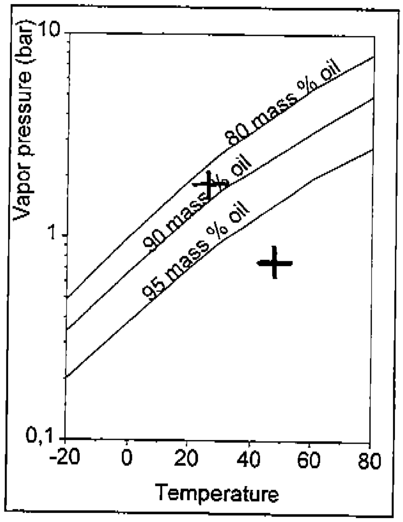

fig. 7 vapor pressure of the oil refrigerant mixture /4/

During the off-cycle the refrigerant is moving through the capillary tube as well as through the hermetic compressor (the valves of this particular device were not entirely closed) to achieve a pressure equalization. Therefore we notice refrigerant actually flowing backward through the compressor. But for giving quantities of this flow the resolution of the mass flow sensor is too low.

During the pressure equalization the components under high pressure which contain liquid (condenser and filter dryer, see figure 8), are being cooled by evaporating refrigerant. The evaporation temperature depends on the actual pressure of the condenser and goes down to a minimum of -5 °C in the filter dryer. The vapor then moves through capillary tube and compressor to the evaporator which is at this point of time quite cold (about -10 to -5 °C) and condenses, adding heat to the evaporator. Also a amount of refrigerant is going into solution with the oil in the compressor can. When the temperature of the evaporator finally rises to 5 °C by the heat load in the refrigerated cabinet (here heat conduction through the walls) the compressor is being switched on.

In figure 9 we see the dynamics of the pressures. Due to the low amount of vapour passing through the capillary tube the pressure in the condenser raises sharply and the evaporating pressure rapidly decreases. With a pressure of about 4.3 bar the refrigerant starts condensing and the mass flow rate into the evaporator increases. As heat is added to the condenser the temperature and therefore the pressure in it goes up. The speed of the pressure raising is a function of heat capacity and heat transfer in the condenser. After the compressor has been switched off, it takes 4 minutes for the pressure to equalize, first the pressure of 1.67 bar is reached in the system and after another 7 minutes (the time when the compressor is switched on again) it has risen to 1.85 bar. This ocures because the evaporator temperature rises and the pressure of the system equalizes to the vapour pressure in the evaporator.

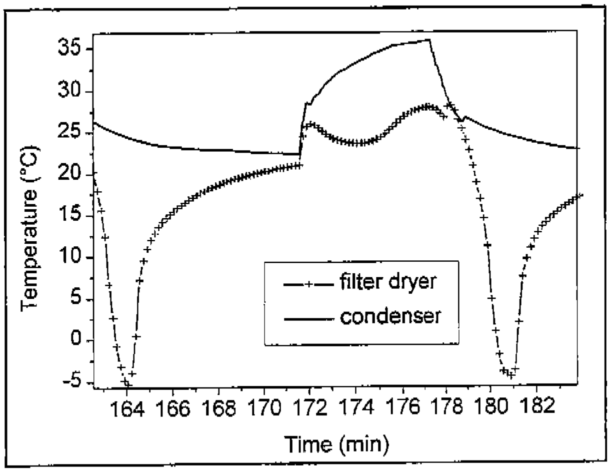

fig. 8 temperatures in condenser and filter dryer vs. time

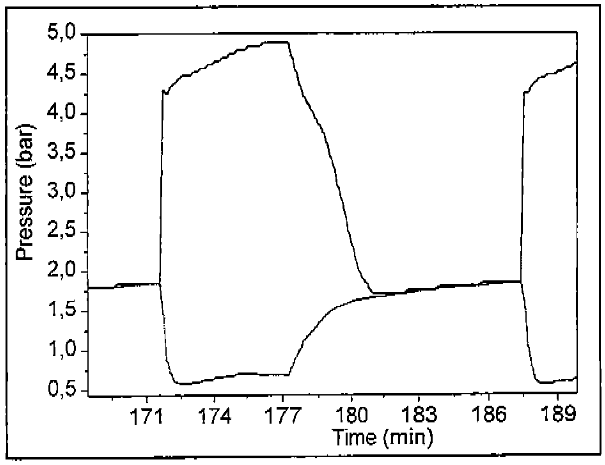

fig. 9 Pressures in suction and discharge line of compressor

8 CONCLUSIONS

By taking data on the test rig which was described here, we were able to show the dynamics of the refrigeration cycle of a household refrigerator during on / off cycling mode. In order to program a simulation software one has to make simplifying assumption. This data taken has shown, that for this refrigerator with a small charge of refrigerant the change of the amount of refrigerant circulating in the cycle must enter into the model. The losses due to the migration of refrigerant are lower than for refrigerators with a higher charge but still effecting the efficiency of the refrigerator.

In the next stage of this work the simulation software will be programmed and the data obtained compared to the data from the test rig. In order to keep the model easy to handle and CPU times low, the effect of simplifying assumptions has to be studied.

9 REFERENCES

/1/ F. X. Eder Moderne Meßmethoden der Physik
Deutscher Verlag der Wissenschaften, 1956

/2/ EPA Refrigerator Analysis Program
United States Environmental Protection Agency
Washington, D.C. 20460

/3/ Refrigeration oil 4323 /Isobutane vapour pressure diagram
Deutsche Shell AG, PAE - Labor LFO, Hamburg

/4/ Compressor map KV075N05 (R600a)
or refrigerator KS1875E
ORON Hausgeräte GmbH
Niederschmiedeberg